Agricultural Water Management 216 (2019) 273–283

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Sub-surface drip fertigation with conservation agriculture in a rice-wheat system: A breakthrough for addressing water and nitrogen use efficiency

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ARTICLE INFO

Keywords:
Conservation agriculture
Direct seeded rice
Subsurface drip irrigation
Fertigation
Irrigation water productivity
Lateral spacing and depth
Net returns
Nitrogen use efficiency

ABSTRACT

The future of the South Asia's rice-wheat (RW) production system is at stake due to continuously depleting aquifers and increasing pressure on underground water under projected climate change scenario. Conventional management factors such as flood irrigation, intensive tillage and residue burning are threatening sustainability of RW system. With increasing adoption of conservation agriculture (CA), sub-surface drip fertigation (SSDF) provides an exceptional opportunity for complementing irrigation water saving benefits. Presently, there is no research evidence on optimum spacing and depth for drip laterals in a CA (direct drilling and residue mulch) based RW system around the globe. This study was therefore, planned to evaluate effects of residue mulch, different spacing and depths of laterals for SSDF on crop yield, irrigation water productivity (WPi), nitrogen use efficiency (NUE) and net returns for CA based RW system in a silt loam soil in northwestern India. Drip laterals were spaced either at 33.75 cm or 67.5 cm, and installation depths were 0, 15 or 20 cm beneath the soil surface and compared with conventional and zero tillage based flood-irrigated RW systems. Grain yield and irrigation water input in rice and wheat were generally similar under different SSDF treatments. Irrigation water savings were 48–53% in rice and 42–53% in wheat under combination of SSDF and CA compared to flood irrigation system. A similar trend in WPi was recorded in both the crops. Residue mulch contributed to higher irrigation water savings, wheat yield and WPi compared to no mulch. Both rice and wheat needed 20% less N fertilizer under SSDF system to obtain grain yields similar to that under flood irrigated crops. Net returns from SSDF system with 67.5 cm lateral spacing were significantly higher compared to flood irrigation system. In conclusion, SSDF system having laterals spaced at 67.5 cm and installed at 15 cm depth provides tangible benefits for substantial saving in irrigation water and energy and increasing NUE and net income for CA based RW system in South Asia.

1. Introduction

Rice (*Oryza sativa* L.) - wheat (*Triticum aestivum* L.) (RW) is the most important cereal based cropping system for food security and livelihood for millions of people, and is practiced on 13.5 million ha in the Indo-Gangetic Plains of South Asia (Ladha et al., 2009). Sustainability of RW system continues to be adversely impacted by the practice of puddling the soil before transplanting rice-seedlings. Traditional RW system consumes large amount (1800–2400 mm) of irrigation water, and is energy and labor intensive, and deteriorates soil health (Chauhan et al., 2012; Jat et al., 2017). The sustainability of the RW production systems of South Asia has become a major concern owing to alarming depletion of water table, stagnating or declining productivity growth and diminishing economic returns (Humphreys et al., 2010). Since early 1970s, there has been a steady decline in groundwater table in most of the RW area of North-West (NW) India (Humphreys et al., 2010). Moreover, climate change will future increase water demand globally by about 40% of the water needed for irrigation without global warming thereby reducing water availability in areas where irrigation is most needed (Fischer et al., 2007). Under the emerging scenario of acute shortages of water, in future it is imperative that we focus our efforts to develop alternative efficient approaches for water use in

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https://doi.org/10.1016/j.agwat.2019.02.019
Received 9 June 2018; Received in revised form 7 February 2019; Accepted 9 February 2019
Available online 15 February 2019
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irrigated RW system in NW India (Yadvinder et al., 2014a).

Scented (*Basmati)* rice is known for its aromatic quality and high economic value as it generates about three times higher price than coarse rice. Around 65% of total global supply of scented rice is contributed by India and earned foreign exchange of US$4.25 billion in 2014-15 (APEDA, 2015). Scented rice occupies about 20% (2.1 million ha) of total area under RW system in India and the NW states (Punjab, Haryana and Western Uttar Pradesh) account for > 90% of its total production in India and has been promoted as water use efficient alternative in the RW system. Scented rice responds well to dry direct seeding (DSR) which has been identified as one of the alternative to puddled transplanted rice (PTR) to address the issues of growing shortages and increasing costs of labor, water and energy scarcity in NW India (Chauhan et al., 2012). Other agronomic practices to save irrigation water in RW system include cultivation of short duration cultivars, shifting planting time of rice towards period of low evaporation demand, zero tillage and straw mulching (Yadvinder et al., 2014a). Crop residues regulate soil temperature, improve soil health and increase crop yields in DSR and wheat (Jat et al., 2017; Yadvinder et al., 2014b). The other approaches suggested saving water and increase water productivity (WP) in different crops includes change from flood irrigation systems to micro-irrigation systems (Ayars et al.,1999; Yadvinder et al., 2014a). Drip irrigation has now been considered economically viable option for field row crops, such as maize, rice and wheat (Chen et al., 2015; Lamm et al., 1997; Sharda et al., 2017). However, uptake of these water saving options has remained slow for field crops in general and RW system in particular due to their field applications (surface drip) issues with conventional tillage based management systems wherein drip laterals has to be removed and placed at multiple times due to several operations during the growing season.

Compared to surface drip fertigation (SDF), subsurface drip fertigation (SSDF) system eliminates necessity of anchoring laterals during the crop-growing season and thus laterals have longer economic life under SSDF system (Ayars et al., 1999). The SSDF system limits evaporation from the soil, allows better delivery of water and nutrients directly to the root zone which leads to efficient fertilizer application, discourages weed growth and reduces labour cost, and it is easier to perform cultural farming practices in SSDF compared to SDF (Ayars et al., 1999). Conservation agriculture (CA) based cereal rotations (rice-wheat, maize-wheat) allows crop residue recycling (which are otherwise burnt), saves irrigation water, lowers energy use and increases farmers profit (Gathala et al., 2013; Jat et al., 2014) and complement the use of SSDF system.

The spacing and depth of lateral driplines in SSDF system need optimization for a double cropping system. The lateral spacing should be selected to provide the flexibility and suitability of using the same irrigation network for both the crops in a given cropping system without vital replacement and modifications. Adoption of similar row/bed spacing for the two crops in a system may be advantageous, provided that the crops produce adequate yields under that spacing (Ayars et al., 1999). The soil (texture, hydraulic properties and density), climate characteristics and crop rooting characteristics also affect the required lateral spacing and depth, Researchers (Lamm et al., 1997; Ayars et al., 1999) used dripline spacing of 140–150 cm for maize (one dripline for every two crop rows) on fine-texture soils in USA. Sharda et al. (2017) used surface dripline spacing of 50 cm for rice for achieving higher yields compared to flood irrigation. Other studies (Chen et al., 2015; Chouhan et al., 2015; Wang et al., 2013) laid driplines at a spacing of 50–60 cm depending on row width for SDF/SSDF system in wheat on fine-textured soils. Dripline depths ranging from 15 to 70 cm were found to be acceptable for optimum maize production with no significant differences in WP (Lamm et al., 1997). Studies have also shown that application of fertilizer along with drip irrigation improves nutrient use efficiency while reducing fertilizer usage and nitrogen losses as leaching and volatilization (Hagin et al., 2003 and references therein).

Most of the earlier studies on SDF or SSDF system are based on individual crops and not system based. Scientific information on the SSDF system for the important RW cropping system is not available from South Asia as well as other parts of the globe. We hypothesized that development of SSDF technology will reduce irrigation water consumption, and increase irrigation water productivity (WPi) and nitrogen use efficiency in CA based rice-wheat system. The objectives of this study were: (1) to optimize the spacing and depth of laterals for SSDF system under CA based management in relation to grain yield, water and energy saving, and WPi, and (2) to evaluate the effects of N fertigation on crop yields and N use efficiency in CA based scented rice-wheat cropping system in NW India.

2. Methods

2.1. Experimental site

A field experiment was conducted for 2 years (2014-15 and 2015-16) to optimize the precision water and nitrogen management options using subsurface drip fertigation (SSDF) under CA based RW cropping system at Borlaug Institute for South Asia (BISA)-CIMMYT, Ladhowal (30.99 °N latitude, 75.44 °E longitude, 229 m ASL), Punjab, India. The region is characterized by a sub-tropical and semi-arid climate with a hot dry summer (March-June), wet monsoon season (late June-mid September) and a cool, dry winter (October-February). Average annual rainfall is 734 mm (44% of pan evaporation) of which about 80% is received during the monsoon. The soil (0–15 cm layer) of the experimental site was silt loam in texture (34% sand, 46% silt and 20% clay) with pH 8.3 (1:2 soil: water), electrical conductivity 0.51 dS m^{-1}, Walkley-Black organic C 7.4 g kg^{-1}, Olsen P 14.6 mg kg^{-1} and NH_4OAc extractable K 149 mg kg^{-1}. Infiltration rate measured using double ring infiltrometer was 6.75 mm h^{-1} and water holding capacity of soil was 23.3% (dry weight basis). At the start of the experiment, soil bulk density was 1.47 Mg m^{-3} at 0–10 cm depth. Before laying out the experiment, field was under RW system for the last five years.

2.2. Weather during the experimentation

Rainfall was measured daily using a Davis weather station installed at the experimental site (Fig. 2). Other meteorological data (daily pan evaporation, maximum and minimum air temperature) were collected (Fig. 3) from the Punjab Agricultural University (PAU) weather station situated in close vicinity of the experimental site.

2.3. Experimental design and treatments

After the harvest of wheat in April 2013, the field was laser leveled and the drip irrigation system was installed in November 2013. To stabilize the soil in experimental plots, a general (cover) crop of well-fertilized wheat was raised prior to the execution of experimental treatments in June 2014. A randomized complete block design with four replications was used in each season. Eight treatments with selected combinations of tillage, residue management, irrigation method, and different spacing and depth of drip irrigation laterals were randomly assigned to each replication. The selection of lateral depths for SSDF system in RW system was based on the results from a preliminary exploratory study, which suggested similar wheat yield for 0, 15 and 20 cm lateral depths but significant yield reduction at 25 cm depth.

The details of treatment are given in Table 1. The treatments included in this study were; (T1) zero till dry-seeded rice and zero till wheat using surface drip irrigation with laterals spaced at 33.75 cm and retaining 25% of wheat stubbles and 100% of rice residue, ZTRW + R + $SDF_{33.75}$; (T2) ZTRW with subsurface drip irrigation with lateral spaced at 33.75 cm at 15 cm depth, and all the residues of both wheat and rice removed, ZTRW-R + $SSDF_{33.75\text{-}15}$; (T3) same as T2 above but

Table 1
Treatments details and abbreviations used in the study.

Treatment ID	Tillage and residue management		Irrigation scenario and depth/spacing of lateral in both rice and wheat	Treatment abbreviation
	Rice	Wheat		
T1	ZTDSR, wheat residue (25%)	ZTW (+R), rice residue (100%)	Surface drip, laterals spaced at 33.75 cm	ZTRW + R + $SDF_{33.75}$
T2	ZTDSR, wheat residue removed	ZTW (-R), rice residue removed	Sub-surface drip (SSD), laterals spaced at 33.75 cm at 15 cm depth	ZTRW-R + $SSDF_{33.75-15}$
T3	ZTDSR, wheat residue (25%)	ZTW (+R), rice residue (100%)	Sub-surface drip (SSD), laterals spaced at 33.75 cm at 15 cm depth	ZTRW + R + $SSDF_{33.75-15}$
T4	ZTDSR, wheat residue (25%)	ZTW (+R), rice residue (100%)	Sub-surface drip (SSD), laterals spaced at 33.75 cm at 20 cm depth	ZTRW + R + $SSDF_{33.75-20}$
T5	ZTDSR, wheat residue removed	ZTW (-R), rice residue removed	Sub-surface drip (SSD), laterals spaced at 67.5 cm at 15 cm depth	ZTRW-R + $SSDF_{67.5-15}$
T6	ZTDSR, wheat residue (25%)	ZTW (+R), rice residue (100%)	Sub-surface drip (SSD), laterals spaced at 67.5 cm at 15 cm depth	ZTRW + R + $SSDF_{67.5-15}$
T7	Zero-till (ZT) direct seeded rice (DSR), wheat residue removed	ZT wheat, rice residue	Flood	ZTRW + R + FI
T8	Conventional till (CT) PTR, wheat residue removed	CT, rice residue removed	Flood	CTRW-R + FI

retaining 25% of wheat stubbles and 100% of rice residue, ZTRW + R + $SSDF_{33.75-15}$; (T4) same as T3 above with laterals placed at 20 cm depth, ZTRW + R + $SSDF_{33.75-20}$; (T5) same as T2 with 67.5 cm lateral spacing, ZTRW-R + $SSDF_{67.5-15;}$ (T6) same as T3 with lateral spacing of 67.5 cm, ZTRW + R + $SSDF_{67.5-15}$; (T7) ZT DSR- ZTW with residue retention using flood irrigation, ZTRW + R + FI; (T8) conventional puddled transplanted rice (PTR) followed by conventional till wheat after removal of all residues of both the crops and flood irrigation, CTRW-R + FI.

The size of each plot was 70.47 m^2 (4.05 m × 17.4 m). ZTDSR-R received 60 kg N ha^{-1} as the recommended rate for Pusa 1509 (short duration scented rice) by Punjab Agricultural University, Ludhiana, India. Rate of fertilizer N applied in flood irrigated (FI) DSR (T7) was 75 kg N ha^{-1} (25% more than recommended for conventional puddled transplanted rice in T8. In rice, FI- PTR/ZTDSR treatments received recommended dose of N as urea (minus the 12 kg N ha^{-1} added through DAP) in two equal splits at 35 and 63 days after transplanting. In drip irrigated treatments, 80% of the recommended N as urea (minus N added through DAP) was applied through irrigation (fertigation) at weekly intervals in six equal splits staring at 21 DAS. To wheat, recommended rate of N (120 kg ha^{-1}) was applied in T7 and T8, while all the drip irrigation treatments (T1-T6) received 80% of the recommended N. To FI wheat plots recommended dose of N (120 kg N ha^{-1}) as urea (minus the 24 kg N ha^{-1} added through DAP) was applied in two equal splits at 21–25 and 50–55 days after sowing. In drip irrigated treatments, 80% of the recommended N as urea (minus N added through DAP) was applied through irrigation (fertigation) at weekly intervals in seven equal splits staring at 21 DAS. Fertilizer N was applied in 7 split doses in drip irrigated treatments, while the recommended N dose (minus 24 kg N ha^{-1} applied as DAP at sowing) was applied as broadcast in two equal splits at 25 (crown root initiation-CRI, at 1st irrigation) and 55–58 DAS (maximum tillering-MT, at 2nd irrigation) in T7 and T8 treatments.

In residue retention (+R) treatments, wheat at maturity was manually harvested at 10–12 cm above the ground level adding about 1.5- 2.0 t ha^{-1} of standing wheat stubbles. In + R plots, rice was also manually harvested at about 30 cm above the ground level to simulate combine harvesting and all loose rice residue was returned to the same plots after separating grains. Total amount of rice residue in different + R plots ranged from 6.0 to 6.5 t ha^{-1} in two years of study. In -R plots, both wheat and rice were harvested at the ground level and all the residue was removed from the designated plots.

2.4. Installation of drip irrigation system

The drip irrigation system consisted of polyethylene laterals with an inside diameter of 16 mm and were laid parallel to crop rows. The laterals were provided with in-line emitters of 2.0 L h^{-1} capacity at a pressure of 135 kPa and spaced at 30 cm, so that the complete plot area was wetted. Subsurface driplines at specific depth were laid by using two row tractor operated drip laying machine with depth control mechanism developed by BISA-CIMMYT, Ludhiana, Punjab, India (H.S. Sidhu, personal communication). There were two lateral spacing at 33.75 and 67.5 cm apart and two depths of laterals installed 15 and 20 cm below the soil surface. Each dripline served 1.5 rows (33.75 cm) three rows (67.5 cm) of rice or wheat crop. Ground water for the SDF system was filtered using a hydro cyclone filter coupled with 100-micron screen filter fitted at the source of irrigation. A Venturi injector was used for fertilizer application through SSDF and suction was created due to the difference between its upstream and downstream pressures. It draws stock solution into water line at the desired injection rate. The schematic diagram of rice crop showing lateral spacing (a) 33.75 cm, and driplines installed at surface, 15 cm and 20 cm depth, and (b) 67.5 cm, and driplines installed at 15 cm and 20 cm depth (Fig. 1).

In both rice and wheat, irrigation was applied on the basis of soil

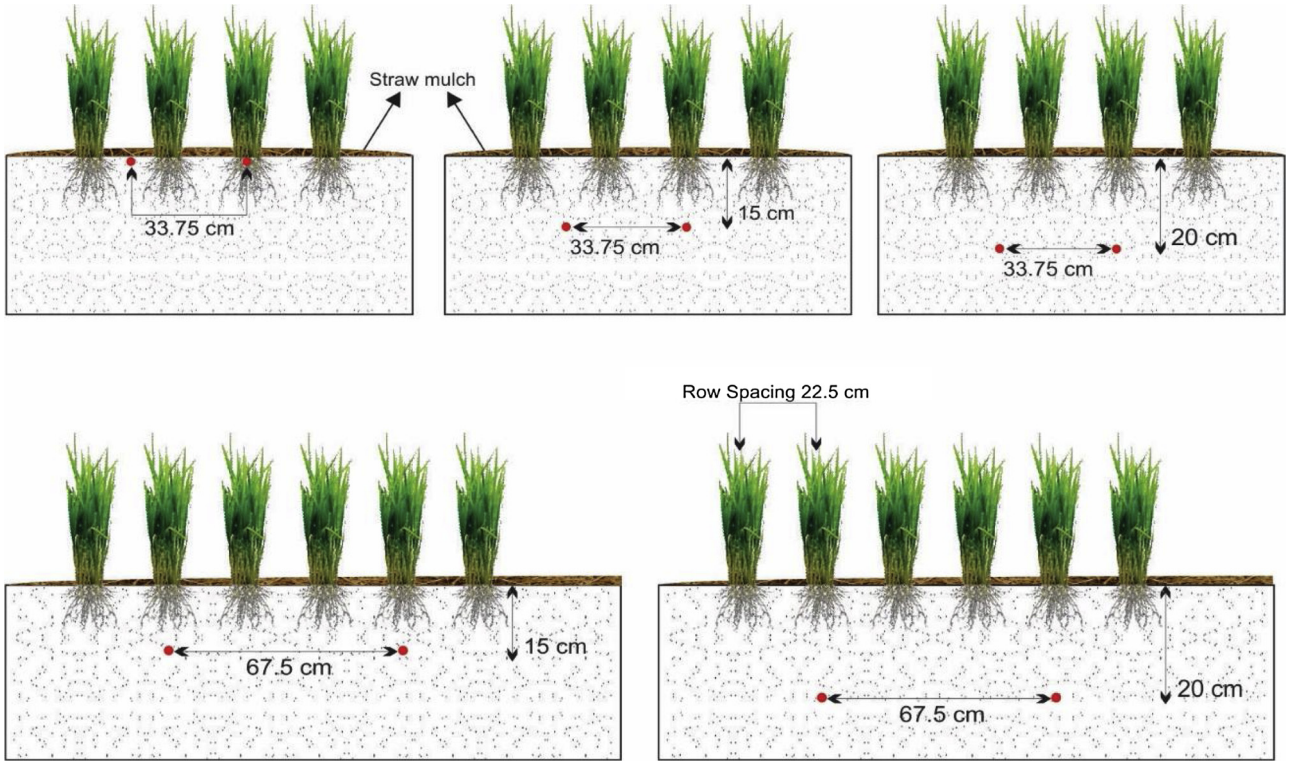

Fig. 1. Schematic diagram of rice crop in straw mulch plots with lateral spacing (a) 33.75 cm and, driplines installed at surface, 15 and 20 cm depth (b) 67.5 cm, and driplines installed at 15 and 20 cm depth.

moisture potential (SMP) using tensiometer (IRROMETER, River-side, California) installed at 15 cm soil depth mid-way between the two crop rows in the centre of each plot. To ensure optimum germination and seedlings establishment, rice was irrigated frequently from sowing until the 3–4 leaf stage (approx. 4 weeks after sowing), and subsequent irrigations were scheduled whenever average SMP decreased to -15 + 1 kPa. All wheat treatments received a common irrigation (70 mm in flood and 10 mm in SSDF treatments) at the CRI (21–25 days after sowing, DAS), (70 mm in T7 and T8 only around MT stage) and subsequent irrigations were applied to a given treatment whenever mean SMP decreased to -35 + 1 kPa. In FI treatments, irrigation water was delivered to each plot, one at a time, using PVC pipe to avoid conveyance losses. Irrigations to each treatment were controlled manually from a manifold that has a flow meter. All the four replications of a particular treatment received similar amount of irrigation at the same time.

2.5. Crop management

2.5.1. Rice

Conventional till plots were flood irrigated (about 75 mm) prior to wet-tillage. Prior to the PTR (T8), there were two discings and one spring tyne tiller followed by wet tillage (puddling) comprising two tillers and two plankings (leveling by dragging a heavy metal bar)

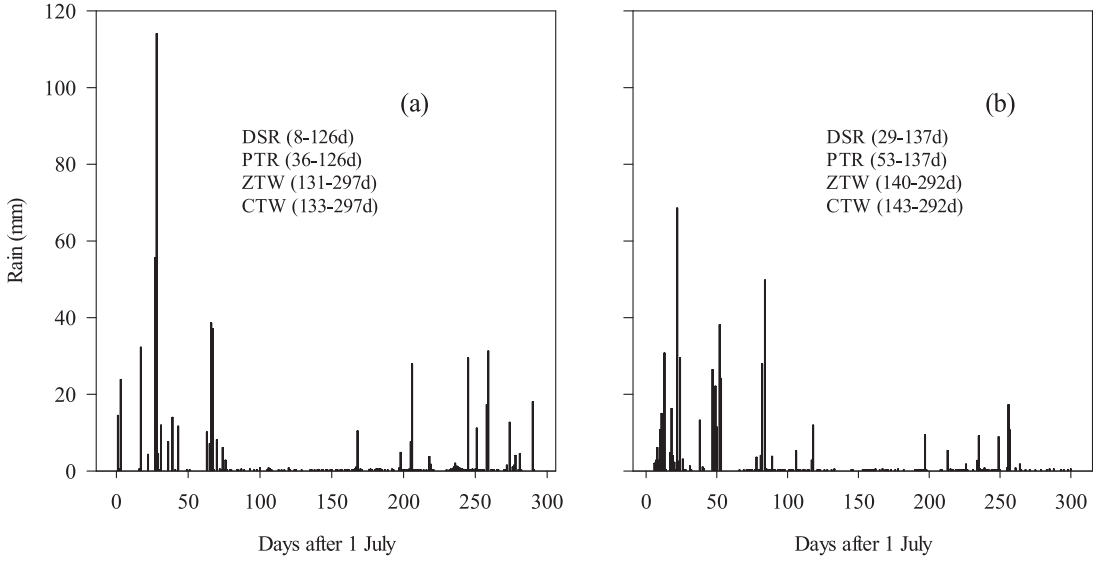

Fig. 2. Daily rainfall during rice and wheat growing season each year (a) 2014-15 and (b) 2015-16.

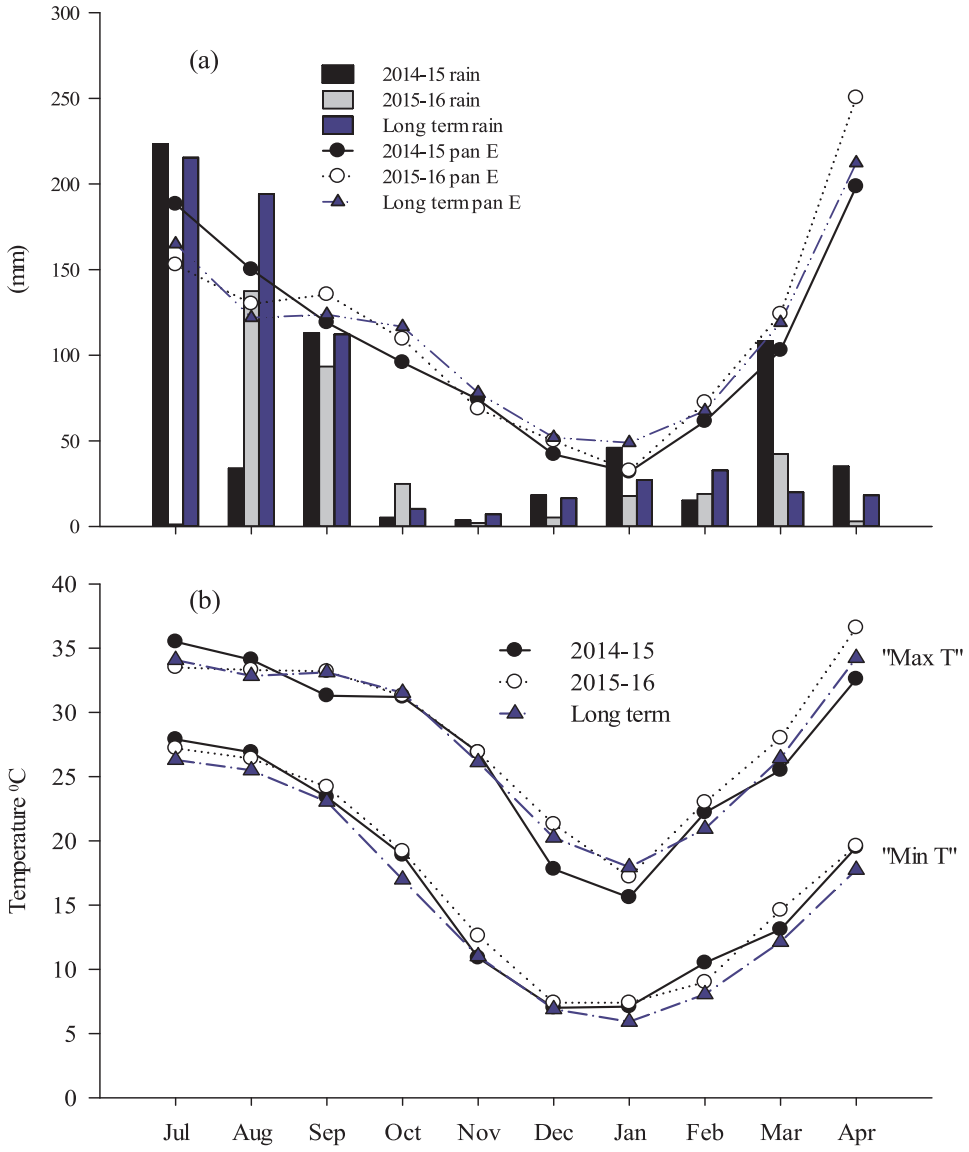

Fig. 3. Monthly mean (a) total pan evaporation and rainfall, and (b) maximum and minimum temperature during 2014–15, 2015–16, and the long term average (1970–2013).

operations. Both rice and wheat were sown with a row spacing of 22.5 cm. The DSR scented rice (Pusa 1509) was sown on 8th July in 2014 and 29th July in 2015 by drilling seed at field capacity moisture regime using a seed rate of 20 kg ha^{-1} at a depth of 2–3 cm, using a Turbo Happy Seeder (Sidhu et al., 2015) with a inclined plate seed metering system. The rice nursery for the PTR treatments was seeded on the date of DSR. Twenty-eight- and 24-day old rice seedlings were transplanted manually in rows 22.5 cm apart with plant-to-plant spacing of 15 cm in PTR plots on 5th August 2014 and 22nd August 2015, respectively. A basal dose of 26 kg P as diammonium phosphate (DAP) and 25 kg K ha^{-1} as muriate of potash (MOP) was applied at transplanting/seeding to all the plots. After the harvest of each crop, driplines from SDF plots were removed and re-laid immediately after the seeding of next crop in the RW system. The crop in DSR treatments was sprayed once with 1% ferrous sulphate solution (250 l ha^{-1}) at 15 DAS to correct Fe deficiency symptoms (yellowing or chlorosis of the interveinal area of leaves). Rice crop were manually harvested at physiological maturity on 3rd November 2014 and 14th November 2015.

2.5.2. Wheat

As in case of rice, CT plots were flood irrigated (about 75 mm) prior to seed bed preparation for wheat. The seed-bed was prepared using two operations each of discing, tiller and planking. Both CT and ZT wheat (HD 2967) was sown at 100 kg ha^{-1} at 3–4 cm depth with a Turbo Happy Seeder (Sidhu et al., 2015). Before sowing of wheat, rice residues were manually spread in residue retention treatments in both the years of study. In 2014-15, ZT and CT wheat was sown on 8th November 2014 and 10th November 2014, respectively. In 2015-16, wheat in the ZT and CT treatments was sown on 17th November 2015 and 20th November 2015, respectively. The CT wheat required additional time for tillage operations, while ZT wheat was direct seeded without any tillage operation. A basal dose of 26 kg P as DAP and 25 kg K ha^{-1} as MOP was drilled along with seed at sowing to all the plots. Recommended practices were used for managing weeds, pests and disease stresses in both wheat and rice crops. Wheat crop was manually harvested (about 10–12 cm above ground level) at physiological maturity on 23 April 2015 and 17 April 2016.

2.6. Observations and calculations

2.6.1. Irrigation water input

The volume of water applied for each irrigation was measured with

the help of water meter (Dasmesh Mechanical Works, Punjab, India) fitted to the delivery pipe close to the experimental plots. Total amount of irrigation water (mm) applied was computed for each crop.

2.6.2. Grain yield and irrigation water productivity

At maturity, grain and straw yields were determined on an area of 10 m^2 in the middle of each plot by manually cutting the plants at ground level. Grain moisture content was determined by oven drying subsamples at 60 °C. Grain yield was expressed as t ha^{-1} at 12 and 14% grain moisture content in wheat and rice, respectively. WP_I was computed as the ratio of grain yield (kg ha^{-1}) to total irrigation water applied (m^3 ha^{-1}) to rice and wheat and is reported as kg m^{-3}.

2.6.3. Partial factor productivity on nitrogen

Partial factor productivity of applied nitrogen (PFP_N) is the grain yield obtained per kg of applied N and was expressed as kg grain kg^{-1} of N applied in each treatment. The PFP_N provides an integrative index of that quantifies grain yield relative to utilization of all N resources in the system, including indigenous soil N and fertilizer N.

2.7. Economic analysis

Partial budgeting was used to determine the economics of the subsurface drip irrigation system. Partial budget is a useful at depicting farmer's financial effects by considering only parts of the farm business that would be affected. In our partial budget, the net returns were the additional revenue that would result from using the SSD irrigation system. The variable costs used in the analysis included the costs of operations (e.g. nursery raising, tillage for seed bed preparation, seeding, harvesting, threshing) and inputs (seed, irrigation, fertilizers, agrochemicals and labour) for raising the crops (Table 2). The economic analysis did not include fixed costs such as land value and interest. All inputs and technologies used in the enterprise budget were as per the recommendations of Punjab Agricultural University (Table 2). The following assumptions were used in our partial budget analysis.

To perform economic analysis, number of labors required for seeding, transplanting, weeding, pesticide, herbicide and fertilizer application and harvesting, etc., were recorded. The time (h) required to complete each field operation in each treatment was recorded and expressed as person-days ha^{-1}, considering 8 h to be equivalent to 1 person-day. Similarly, the time (h) required by a tractor drawn machine/implement to complete a field operation such as tillage, seeding, and harvesting was recorded, and expressed as h ha^{-1}. The prices of inputs such as seeds, fertilizers, pesticides, fuel, herbicide, etc., were recorded. For irrigation costs, the charges fixed by the electricity board of Punjab government (Rs. 0.30 per kWh of electricity) were used plus the cost of labour used for irrigation application. Total number of irrigations ranged from 44 to 53 for rice and 16 to 21 for wheat under SSDF treatments during the two years of study. Labor cost was set at Rs. 350 per man-day. Cost of drip irrigation system was calculated after considering 80% subsidy provided by the Govt of India on the actual cost (Rs. 250 × 10^3 ha^{-1}). The cost incurred on the drip system was calculated considering the life span of 20 years for main, sub-main, venturi, and pump. Life of surface and subsurface drip irrigation system was considered as 8 yrs and 15 yrs, respectively. Depreciation cost of drip irrigation system was considered as 10%. The gross returns (GR) included income from sale of rice and wheat grain and wheat straw. The minimum support price (MSP) fixed by the government for basmati rice and wheat grains was used for calculating gross returns (Table 2). Net return from each treatment was calculated after subtracting variable costs from the calculated GR. Indian Rs. was converted to US$ based on a conversion rate of Indian Rs. for 1 US$.

2.8. Statistical analysis

The data were analyzed by analysis of variance (ANOVA) technique for completely randomized block design using SAS 9.1 software (SAS Institute, Cary, NC). Differences between treatment means were compared using Fisher's least significant difference (LSD) tests at the 5% probability level.

Table 2
Cost of key inputs and outputs used for economic analysis in rice-wheat cropping systems.

Particulars	Amount (Rs)
Price of rice seed	Rs 75.0 kg^{-1}
Price of wheat seed	Rs 35.0 kg^{-1}
Urea	Rs 5.44 kg^{-1},
DAP	Rs 24 kg^{-1},
Preparation of PTR/CTW plots	Rs 5500 ha^{-1}
Sowing of DSR/wheat (without mulch)	Rs 1500 ha^{-1}
Sowing of DSR/wheat (with mulch)	Rs 2500 ha^{-1}
Seed treatment in rice	Rs 70 ha^{-1}
Seed treatment in wheat	Rs 140 ha^{-1}
Transplanting of rice (manual)	Rs 5500 ha^{-1}
Weedicide in DSR (including pre plant weedicide)	Rs 4425 ha^{-1}
Weedicide in transplanting of rice	Rs 625 ha^{-1}
Weedicide in wheat	Rs 1175 ha^{-1}
Pesticide in rice	Rs 1846 ha^{-1}
Pesticide in wheat	Rs 632 ha^{-1}
Ferrous sulphate spray in DSR	Rs 162 ha^{-1}
Cost of irrigation	Rs 100 ha^{-1}
Labour cost	Rs 320 day^{-1}
Combine harvester and straw reaper in wheat	Rs 6750 ha^{-1}
Combine harvester in rice	Rs 2500 ha^{-1}
Market price of wheat straw	Rs 2500Mg^{-1}
*Drip cost for 33.75 cm spacing (with 80% subsidy and 15-year life)	Rs 2769 ha^{-1}
*Drip cost for 67.5 cm spacing (with 80% subsidy and 15-year life)	Rs 1530 ha^{-1}
*Drip cost for surface (with 80% subsidy and 8-year life)	Rs 5108 ha^{-1}
Drip cost for 33.75 cm spacing (without subsidy and 15-year life)	Rs 13,847 ha^{-1}
Drip cost for 67.5 cm spacing (without subsidy and 15-year life)	Rs 7650 ha^{-1}
Drip cost for surface (without subsidy and 8-year life)	Rs 25,540 ha^{-1}
**Minimum support price of basmati rice	Rs. 32,250 Mg^{-1}
**Minimum support price of wheat	Rs.14,375 Mg^{-1}

1US$ = 66.0 Indian Rupees (Rs); * Drip cost is same for both rice and wheat; **Mean for 2014 and 2015.

3. Results and discussion

3.1. Weather

3.1.1. Rice season

Rainfall during the 2014 (376 mm) and 2015 (257 mm) rice seasons was much lower than the long-term average (June-September) of 532 mm. The pattern of rainfall distribution was also quite different during the two seasons, with low rain in August 2014 and July 2015, and nearly similar rainfall in September 2014 and 2015 (Figs. 2 and 3a). Monthly pan evaporation each rice season was generally similar to the long-term average (Fig. 3a), except for higher than usual values in the months of July and August 2014 and lower than usual in October 2014. As a result, total pan evaporation in June-September 2014 (458 mm) was higher than the long term average (411 mm) but it was similar to that of long term average in 2015 (419 mm). Minimum monthly temperature was 1–2∘C higher than the long term average throughout the rice season each year apart from a similar value in September 2014 (Fig. 3b). Maximum monthly temperatures were generally similar to the long term averages, apart from a higher value in July 2014 and lower value in September 2014.

3.1.2. Wheat season

Total rainfall during the 2014-15 wheat crop was 227 mm, half of which fell in March (Figs. 2a and 3 a), higher than the long term

Table 3
Effect of residue mulch, and drip spacing and flood irrigation system on grain yield (t ha^{-1}) during rice and wheat growing seasons in 2014-15 and 2015-16.

Treatments*	Rice 2014	Rice 2015	Wheat 2014-15	Wheat 2015-16
T1	4.62	4.79	5.60	5.72
T2	4.57	4.66	5.14	5.79
T3	4.59	4.85	5.51	5.70
T4	4.72	4.57	5.32	5.23
T5	5.15	4.83	5.40	5.69
T6	4.79	4.70	5.56	5.48
T7	4.88	4.67	5.07	5.29
T8	4.71	4.40	4.74	4.38
LSD (0.05)	0.42	NS	0.22	0.25

* Refer to Table 1 for treatment details.

November-April average of 122 mm. The 2015-16 wheat season was drier, half of which fell in March (Fig. 2b), with total growing season rainfall of 90 mm. Monthly pan evaporation each wheat season tended to be similar to or lower than the long term average, apart from much lower values in January each year and higher values in April 2015-16. Total pan evaporation (November–April) was 511 and 598 mm in 2014-15 and 2015-16, respectively, than the long term average (578 mm). Mean monthly maximum and minimum temperatures was higher than the long term values during both the year, apart from higher minimum values in February-March during both year, and lower maximum values in April 2014-15 (Fig. 3b).

3.2. Grain yield

Straw mulch (+R) had no significant effect on grain yield of rice (T2 vs T3 and T5 vs T6) (Table 3). Also, most drip irrigation treatments had non-significant effect on grain yield of rice compared to FI (both ZT and CT), except ZTRW-R + SSDF$_{67.5–15}$ (T5) which resulted in significantly higher grain yield compared to CTRW-R + FI (T8) in 2014. Such non-significant effect of small amount of standing wheat stubbles (~2 t ha^{-1}) plus remnant of rice residue (< 2 t ha^{-1}) from previous wheat season on yield of DSR as observed in our study were also reported in similar soil and climatic conditions by Naveen et al. (2016). Since, wheat straw is a valuable cattle fodder for the farmers in the region and 75–80% of the straw is collected from the fields and no response of rice to mulching is a win-win.

Depth of placement of laterals (15 cm vs 20 cm) in sub-surface drip irrigation system showed no significant effect on grain yields of rice. In 2014, at the same dripline depth (15 cm), spacing of laterals at 67.5 cm and residues removal (T5) resulted in significantly higher rice yield than that spacing at 33.75 cm (T2). In 2015, there was no significant effect of any of the treatments on grain yield of rice (Table 3). Ramulu et al. (2016) reported that each dripper line spaced at 80 cm was sufficient for feeding four rice crop rows on a clay loam soil. Results from studies by Nagaraju et al. (2014) and Sharda et al. (2017) revealed that DSR recorded significantly higher grain yield under SDI with laterals spaced at 60 cm with emitters at a distance of 40 cm in DSR compared to FI- PTR. Higher grain yield in SSDF treatments was ascribed to favourable conditions provided for water and N supply under drip irrigation cum fertigation. However, in our study grain yield of DSR was similar in both drip irrigated and FI plots. Well distributed rain during the rice 2015 season (Fig. 2b) further nullified the effect of drip irrigation on crop yields.

In wheat, residue retention as mulch significantly increased the mean grain yield of wheat by 7.2% compared to no residue (T2 vs T3) during 2014-15, whereas on the grain yield was on par during 2015-16 (Table 3). The increase in grain yield of wheat under residue mulch may be ascribed to the positive effects of mulch on soil temperature modifications and soil moisture supply, and improvement in soil quality parameters such as SOC and nutrient availability (Jat et al., 2017; Yadvinder et al., 2014b). Earlier studies (Yadvinder et al., 2014b and references therein) reported greater benefits of straw mulch on grain yield of FI wheat compared to the current study. Probably, the effect of straw mulch on reducing evaporation under SSDF system was small as soil surface remained dry during most of the wheat growing season. Depth of placement of laterals (15 cm vs 20 cm) in drip irrigation system showed no significant effect on grain yield in the first year whereas it was significantly higher at 15 cm depth compared to 20 cm in second year. Using data from a single wheat cropping season, Chouhan et al. (2015) reported 40 cm as optimum depth of lateral for SSDF system on a clay loam soil. Grain yield of wheat was significantly higher in drip irrigated treatments compared to FI (both ZT and CT) in both years (Table 3). SSDF system has been reported to limit evaporation from the soil and allows delivery of water and nutrients directly to the root zone and thus leads to efficient fertilizer application compared to SDF (Ayars et al., 1999). The lower wheat yields after PTR was in part was due to delay in wheat sowing by 3–4 days caused by extra time needed for seed bed preparation relative to ZT wheat under SSDF system. Among the drip-irrigated treatments, there was no significant difference in wheat yield between the 33.75 and 67.5 cm dripline spacing which indicate that driplines spacing at 67.5 cm can be recommended as the cost of installing a drip system would be markedly reduced. Consistent with the results from our study, other researchers (Chen et al., 2015; Chouhan et al., 2015) reported optimum lateral spacing of 60–70 cm for wheat (one lateral for every 3 rows) in terms of achieving maximum yield and WP in wheat on fine-textured soils, which have the capability of moving water long distances from drip emitters.

Results from our study show that to attain the similar crop yields under SSDF and FI systems, the amount of fertilizer N needed for rice and wheat under SSDF system was 20% lower than in FI crops. Fertigation using SSDF can effectively manage the placement and availability of nutrients. Continuing to apply the same N rates used in conventional management systems to fertigated crops would probably result in lower N use efficiency by the crop and increased losses of N to the environment. Timing the fertigation to coincide with periods of demand from the crop (growth curve nutrition) is a common method of maximizing fertilizer use efficiency in many crops. In our study, fertilizer N was applied at weekly intervals compared to that applied in 2–3 splits in FI treatments. Based on experience in other crops, the N rate is likely to be in order of 20–50% lower than rates in conventional management systems (Hagin et al., 2003 and references therein). Nagaraju et al. (2014) reported that fertigation resulted in 50 per cent fertilizer saving in rice of the recommended 125 kg N ha^{-1}. In regions where rainfall around planting time is fairly reliable, Lamm et al. (1997) advocated that different lateral spacings have not influenced maize yield to warrant the extra cost of a closer lateral spacing. Results from our study also confirm that a 67.5 cm lateral spacing with 15 cm lateral depth is better than a 33.75 cm lateral spacing and a 15 cm lateral depth for irrigated rice-wheat system on the silt loam soil. However, such studies are needed to be evaluated for different soil types, climatic conditions and irrigation availability for their wider applications.

3.3. Irrigation water input

Amount of irrigation water applied to rice through drip system was 53.0 and 43.2% lower compared to CT-FI (1296 mm) and FI-zero tillage flood (1072 mm), respectively in 2014 (Fig. 4). Similar was the trend in 2015 with 47.6 and 42.5% lower irrigation amount in drip irrigation system compared to FI in CT (1109 mm) and ZT rice (1010 mm) (Fig. 4). Results from earlier studies (Ramulu et al., 2016; Sharda et al., 2017) also showed that drip irrigation in DSR resulted in water savings of more than 40–50% compared to FI rice by reducing seepage, deep drainage and evaporation losses as the small amounts of irrigation water were applied for every irrigation at 2–3 day-interval thus keeping

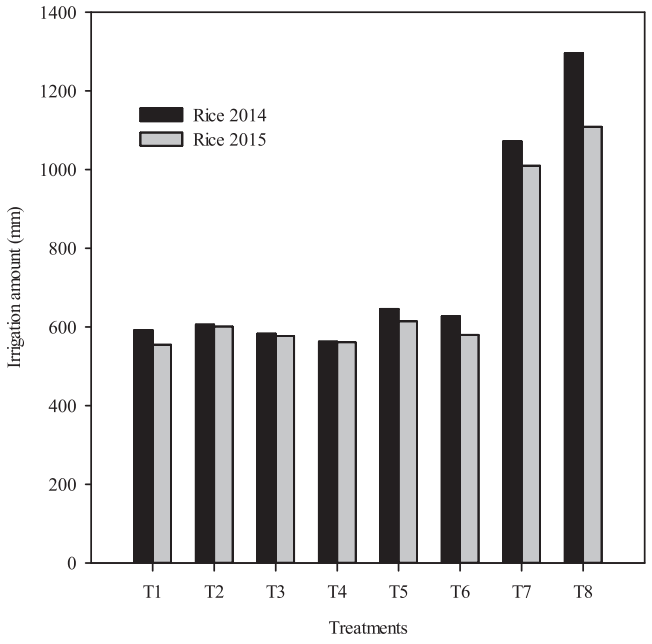

Fig. 4. Effect of residue mulch, and drip spacing and flood irrigation system on irrigation amount (mm) in rice 2014 and 2015 seasons.

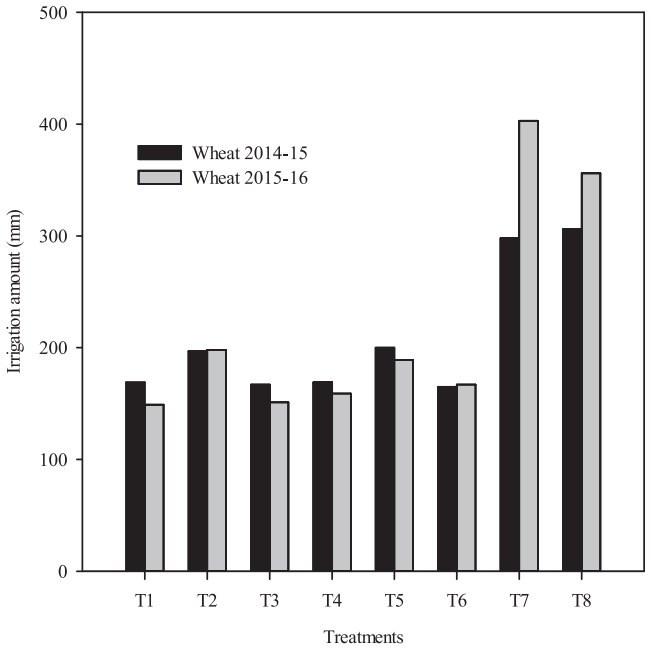

Fig. 5. Effect of residue mulch, and drip spacing and flood irrigation system on irrigation amount (mm) in wheat 2014-15 and 2015-16 seasons.

soil drier. Total amount of irrigation water applied to rice, particularly in FI treatments, was 124 mm more in the year 2014 compared to 2015, as the rains were fewer in 2014. In 2014 and 2015, irrigation water input in rice was 19–83 mm (mean 50 mm) and 34–59 mm (mean 47 mm) more in T5 (laterals spaced at 67.5 cm with no mulch) when compared with other drip irrigation treatments with residue mulch (T1, T3, T4, T6), respectively. The decrease in irrigation water input in residue mulch compared to no mulch plots was possibly due to reduction in evaporation losses. Sharda et al. (2017) reported similar water savings in rice under SDF compared to FI due to lower evaporation and drainage losses under SDF. Effect of lateral depth on irrigation water input in rice was relatively small with 16–20 mm lower water input for 20 cm depth (T4) compare to 15-cm depth (T3).

Residue mulch in wheat reduced the irrigation water applied input by 40.7 and 41.9 mm compared to no mulch in 2014 and 2015, respectively (Fig. 5). Surface residues are known to reduce evaporation losses and conserve soil moisture thereby crops required less amount of irrigation water in wheat (Ram et al., 2013). Like in DSR, amount of irrigation water applied to wheat through drip system was 41.9 and 40.3% lower compared with FI in CT (306 mm) and ZT (298 mm), respectively in 2014-15. Similar was the trend in 2015-16 with 52.6 and 58.1% lower irrigation amount in drip system compared to FI in CT (356 mm) and ZT (403 mm) (Fig. 5). The drip-irrigated crop received water at a shorter interval (2–3 d interval in rice and 8–10 d interval in wheat) subject to weather conditions whereas water was applied at a longer interval in the FI rice and wheat. More water in FI treatments might contribute to percolation losses beyond the active root zone because the amount of water applied at each irrigation is higher than the soil water storage capacity. Consistent with the results from our study, a number of researchers (Chen et al., 2015; Chouhan et al., 2015) have reported significant reduction in irrigation water use with drip irrigation system compared to FI wheat. By increasing application precision and reducing unneeded losses through drainage and evaporation applications, water can be conserved and energy needed for pumping water can be saved. In our study, effects of spacing and depth of laterals on irrigation water input in wheat with straw mulch were generally small in SSDF system. Chouhan et al. (2015) reported that installing the drip irrigation system at 60 cm lateral and with 30 cm dripper spacing provided uniform moisture distribution in the active root zone in wheat and led to large water saving in clay loam soil. Further studies are suggested to compute the complete water balance components under SSDF to report real water savings.

3.4. Irrigation water productivity (WP_I)

WP_I of rice was significantly higher with residue mulch (+R) and for drip irrigation treatments (T1-T6) compared to no mulch (-R) and FI treatments (T7 and T8) in both rice seasons (Fig. 6). Savings in irrigation water due to reduced evaporation under surface mulch resulted in an increase in WP_I over no mulch. WP_I of DSR in drip irrigation

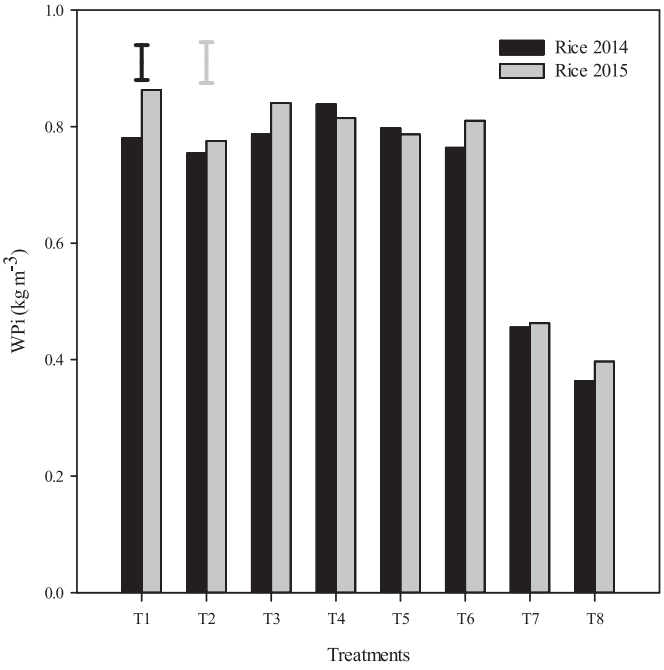

Fig. 6. Effect of residue mulch, and drip spacing and flood irrigation system on irrigation water productivity (WP_i) during rice. Vertical bars (Rice 2014, black) (Rice 2015, grey) are lsd (p = 0.05) for comparing any treatment combinations.

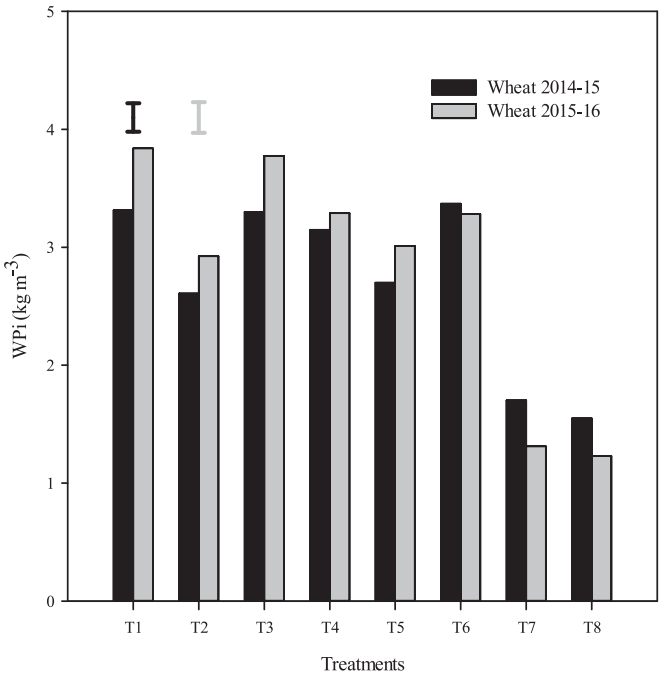

Fig. 7. Effect of residue mulch, and drip spacing and flood irrigation system on irrigation water productivity (WP_i) during wheat. Vertical bars (Wheat 2014-15, black) (Wheat 2015-16, grey) are lsd (p = 0.05) for comparing any treatment combinations.

treatments ranged from 0.75-0.84 kg m^{-3} compared to 0.36-0.46 kg m^{-3} in FI treatments. The findings from this study are consistent with the observations of Sharda et al. (2017) who reported that drip irrigation in DSR resulted in higher WP_I (0.85–0.90 kg m^{-3}) than FI (0.42–0.52 kg m^{-3}) on a sandy loam soil under the similar climatic conditions. Large irrigation water savings in SDF/SSDF compared to flood irrigation with similar or higher crop yields compared to FI resulted in the higher WP_I (Chen et al., 2015). Since grain yield and irrigation water inputs were generally similar at different spacing and depth of laterals in straw mulch treatments, no significant effects were recorded on WP_I of rice in both the seasons.

The WP_I of wheat was significantly higher in drip irrigation treatments compared to FI (both ZT and CT) in both years (Fig. 7). WP_I in wheat in drip irrigated treatments ranged from 2.61 to 3.84 kg m^{-3} compared to 1.23–1.70 kg m^{-3} in FI treatments (Fig. 7). In the drip-irrigated wheat, both irrigation water savings and increased yields resulted in higher WP_I in both the years over FI. The WP_I in wheat was significantly higher with residue mulch compared to no mulch due to higher grain yield and lower irrigation input in both the seasons (Fig. 7). Spacing of laterals at 33.75 cm and 67.5 cm when compared at same depth (15 cm), resulted in similar WP_I in wheat. This study revealed that drip irrigation in DSR has the potential to increase irrigation WP_I by matching the water requirement of crop and reducing deep drainage losses, and generally keeping soil drier and reducing soil evaporation (Ayars et al., 1999).

3.5. Partial factor productivity of nitrogen

NUE described as partial factor productivity of applied N (PFP_N) was significantly affected by drip irrigation and crop establishment of rice and wheat (Table 4). PFP_N in T5 was significantly higher by 30.6 and 9.62% in rice and 33.8 and 52.1% in wheat compared to FI ZT and FI CT treatments (T7 and T8), respectively (Table 4). PFP_N in rice was significantly higher at 67.5 cm lateral spacing (T5) compared to that at 33.75 cm spacing (T2) when residues were removed and laterals installed at 15 cm depth. The PFP_N was significantly higher in all the drip irrigation treatments (T1-T6) compared with both CT and ZT in FI wheat. The results from present study are in contradiction with the observation of Sharda et al. (2017) who did not find any additional advantage of fertigation in DSR, possibly due to high levels of N used in their study. The FI ZT wheat + R (T7) had 13.7% higher PFP_N compared with FI- CT wheat-R (T8). The PFP_N of rice + wheat (RW) system was significantly higher in all the drip irrigated treatments compared with both CT and ZT FI wheat. Both spacing and depth of lateral showed no effect on PFP_N in wheat and RW system. The higher values of PFP_N recoded under SSDF system compared to flood irrigation were mainly due to lower amount of N fertilizer needed to produce similar yields of rice and wheat and in part can be ascribed to higher wheat yields under SSDF system. PFP_N values differ among crops because they differ in their nutrient and water needs. The PFP_N were higher for rice than for wheat. From an extensive review of 93 published studies, Ladha et al. (2005) reported average values for PFP_N were generally higher for rice (62 kg kg^{-1} N) than for wheat (45 kg kg^{-1} N), at least in part due to the higher N content of wheat grain. However, there is a need to determine the optimum rate and timing of N application under SSDF for both rice and wheat crops.

Table 4
Effect of residue mulch, and drip spacing and flood irrigation system on partial factor productivity of nitrogen (PFP_N) in CA-based rice-wheat system (data pooled over two years).

Treatment*	Fertilizer N applied (kg ha^{-1})			PFP_N (kg grain kg^{-1} N applied)		
	Rice	Wheat	RWS	Rice	Wheat	RWS
T1	60	96	156	78.4ab	59.0a	66.5a
T2	60	96	156	77.0b	56.9a	64.7a
T3	60	96	156	78.7ab	58.4a	66.2a
T4	60	96	156	77.5ab	55.0a	63.6a
T5	60	96	156	83.2a	57.8a	67.5a
T6	60	96	156	79.1ab	57.5a	65.8a
T7	75	120	195	63.7c	43.2b	51.1b
T8	60	120	180	75.9b	38.0c	50.7b

Dissimilar alphabet indicate statistically significant differences and similar letters indicate non-significant differences between the values.
* Refer to Table 1 for treatment details.

3.6. Economic analysis of rice-wheat system

Economic benefit is an important consideration when evaluating crop management practices. The results of the current study showed that the variable costs of production in rice and wheat were lower by Rs. 8.12–11.97 thousand ha^{-1} and Rs. 2.62–4.31 thousand ha^{-1} in CA based drip irrigation treatments (T1-T6) than under conventional flood irrigated treatment (T8), respectively (Table 5). The higher variable cost under conventional RW system (T8) was primarily due to high labor and fuel cost for land preparation for and high cost for transplanting seedlings in rice. Similarly, higher variable cost in ZT flood irrigated rice (T7) compared to drip irrigated treatments was due to more cost for irrigation water and labour cost for irrigation application. Gross returns in rice and wheat were significantly higher for SSDF with laterals spaced at 67.5 cm and laid 15 cm below soil surface (T5) compared to treatment with laterals spaced at 33.75 cm and placed at 15 cm (T2) and flood irrigated conventional till (T8) and flood irrigated ZT rice (T7) (Table 5). Gross returns (GR) in SSDF system with laterals spaced at 67.5 cm (T5) were significantly higher compared with conventional flood irrigation system (T8) due mainly to significantly higher yields of rice and wheat (Table 5). Dripline cost is a large portion of the initial SSDF system cost; drip laterals at 67.5 cm and buried at 15 cm or 20 cm depth result in half the number of drip laterals compared with that at 33.75 cm (Table 2). However, in our study, dripline spacing (T4 vs T6) showed relatively small (ca. 4%) effect on total variable cost because 80% of its cost is subsidized. Earlier studies in maize (Camp

Table 5
Economics analysis of different treatments of rice and wheat and rice-wheat system (data pooled over 2 years) with 80% subsidy on drip system.

Treatment*	Variable cost of cultivation (in Rs. X 10^3)		Gross returns (in Rs x 10^3)		Net returns (in Rs x 10^3)		
	Rice	Wheat	Rice	Wheat	Rice	Wheat	Rice + wheat
T1	28.52	28.23	151.87ab	106.31a	123.35b	78.08ab	201.43ab
T2	25.54	25.48	148.85b	102.21b	123.31b	76.74b	200.05ab
T3	26.29	25.89	152.45ab	104.17a	125.86a	78.28ab	204.14ab
T4	26.03	25.95	149.68b	99.29c	123.65a	73.34c	196.99a
T5	24.67	24.21	160.89a	104.06a	136.22a	79.85a	216.07a
T6	25.03	24.73	153.02ab	104.34a	127.99a	79.61a	207.60a
T7	30.02	25.28	153.86ab	96.33d	123.84b	71.05c	194.89b
T8	36.64	28.52	146.91b	84.69e	110.27c	56.17d	166.44c

Dissimilar alphabet indicate statistically significant differences and similar letters indicate non-significant differences between the values.
* Refer to Table 1 for treatment details.

et al., 1997; Lamm and Trooien, 2003) showed that initial installation cost was lower by 30% to 40% when lateral spacing was increased by 100%. The highest net returns (NR) recorded under SSDF system (T1-T6) were owing to the combined effect of higher crop productivity with lesser cost of tillage and labour for seeding than the most prevalent conventional system (T8) (Table 5). Net returns from RW system from T5 were 10.9 and 29.8% higher compared flood irrigated T7 and T8 treatments, respectively. In sugarcane, Sivanappan (1994) reported that net profit of the drip irrigation system was 74% over the profit of the flood irrigation system. Benefit to cost ratio (NR divided by total variable cost) for SSDF system ranged from 3.55 to 4.42 compared to 2.55 for conventional RW system (T8). The NR and benefit to cost ration from SSDF will still be higher when the subsidy is reduced to 25% from 80% considered in the current economic analysis.

Economic analysis by Sharda et al. (2016) showed that although net income for surface drip irrigated rice was lower than for flood irrigation, there was more than 40% irrigation water saving with the drip system under the similar climatic conditions in Punjab, India. Our study demonstrated that drip irrigation in RW system is a potential option for a water-scarce future and to cope up with alarming ground water table depletion (for example RW system in NW India). Under such situations, the policy planners are exploring alternate options to incentivize farmers for more efficient water uses rather than providing free electricity for pumping. For example, the Government of Punjab, India is piloting the direct benefit transfer on electricity (DBTE) to farmers rather than free/subsidized electricity for pumping water for irrigation to economize the water use in intensive RW system wherein drip irrigation technology will be immensely helpful. Moreover, portfolio of SSDF and CA based management have complementarity from technology application and policy (investment/incentive) perspective. Further, under SSDF, the life of drip irrigation system will be doubled due to non-movement of the laterals as well as protection from sun etc which not only help farmers to reduce cost but also to governments to save on subsidies/incentives on drip irrigation. Hence, drip irrigation system will be an economically as well as ecologically viable alternative under both scenarios of (i) current subsidy regime on drip irrigation system (80%) coupled with free electricity or (ii) pricing of water pumping (no electricity subsidy) but incentivizing the water saving technologies in agriculture. The latter option will be more promising and futuristic for impact at scale and contribute to sustainable development goals (SDGs).

4. Conclusions

Our study has provided science based first evidence of using subsurface drip fertigation (SSDF) system as means of saving precious irrigation water, increasing irrigation water productivity and improving N use efficiency in CA based rice-wheat (RW) system. Zero till with straw mulch in SSDF system further helped in irrigation water saving and increasing WP_I over no mulch. The dripline (lateral) spacing of 67.5 cm and a depth of 15 cm were optimum for SSDF in CA based rice-wheat production system on silt loam soil in NW India. Fertigation using subsurface drip irrigation saved 20% of N fertilizer thus increasing N use efficiency compared to flood irrigation. We used a single N rate and a fixed 7-day fertigation schedule in this study. Therefore, optimum N rate and fertigation schedule need to be standardized for both rice and wheat crops to further improve yield and NUE. Our results demonstrated that, it is possible to further improve rice and wheat productivity, irrigation water productivity and N use efficiency, with reduced global warming potential by adopting the drip irrigation system coupled with CA in NW India. The findings from our study have broader implications for dramatically reducing ground water pumping for irrigation to produce similar or higher yields in RW system in NW India and in other regions of South Asia where water table is showing depleting at an alarming rate. Moreover, since energy requirement for pumping of water using drip irrigation (SDF or SSDF) is 50% lower than that of flood irrigation, can be met through solar powered pumps and hence reduces the water footprints significantly. Moreover, the 50% saving in irrigation water by SSDF will contribute to sustainable intensification of RW system. The results of our study provides (i) optimum design of subsurface drip irrigation system for CA based RW system and (ii) provides novel information and first such evidence useful for the researchers, policy planners and farmers.

Acknowledgements

The authors thankfully acknowledge the funding support received from CGIAR Research Program on Wheat Agri-Food Systems (WHEAT), Indian Council of Agricultural Research (ICAR) and Government of Punjab (India). We also acknowledge the contributions of the field staff at BISA and CIMMYT based at Ludhiana, Punjab.

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